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ADAPTIVE STRUCTURES PROGRAMS FOR THE STRATEGIC DEFENSE INITIATIVE ORGANIZATION

Lt.Col. Michael Obal*
The Pentagon
Washington, DC

Dr. Janet M. Sater*
Institute for Defense Analyses
Alexandria, Virginia

Abstract

In the currently envisioned architecture none of the Strategic Defense System (SDS) elements to be deployed will receive scheduled maintenance. Assessments of performance capability due to changes caused by the uncertain effects of environments will be difficult, at best. In addition, the system will have limited ability to adjust in order to maintain its required performance levels. The Materials and Structures Office of the Strategic Defense Initiative Organization (SDIO) has begun to address solutions to these potential difficulties via an adaptive structures technology program that combines health and environment monitoring with static and dynamic structural control. Conceivable system benefits include on-orbit system health monitoring and reporting, threat attack warning and assessment, and improved target tracking and hit-to-kill performance.

Introduction

The Strategic Defense Initiative Organization (SDIO) has undergone a dramatic change in its mission architecture. The system envisioned during the early years was concerned with the destruction of a substantial portion of a massive Soviet attack involving thousands of nuclear re-entry vehicles. Its purpose was to provide sufficient uncertainty to Soviet forces to enhance deterrence. The goal of the new architecture, Global Protection Against Limited Strikes (GPALS), is to prevent from one to, perhaps, hundreds of attacking missiles from reaching their target. This architecture may, however, have difficulty achieving its performance goal than the previously designed systems. The GPALS systems are to be designed to allow no "leakers" - no penetration of US/allies air space by attacking missiles. With the proliferation of nuclear and missile technologies the threat against the US and its allies is of particular concern.

To attain this goal the elements that constitute the GPALS architecture must meet performance and reliability constraints much beyond those of current military weapon systems. The elements must be able to react quickly and perform optimally after remaining dormant for an extended period of time. Two critical components of the GPALS architecture consist of space-based autonomous surveillance and defensive elements. None of these elements will receive scheduled maintenance. Assessments of performance capability due to changes caused by the uncertain effects of natural environmental aging and man-made threats will be difficult, at best. In addition, the system will have limited ability to adjust critical structural components in order to maintain its required performance levels. A solution to these potential difficulties is adaptive structures technology that combines health and environmental monitoring with threat attack warning and assessment capabilities and static and dynamic structural control.

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Several different concepts for "Adaptive Structures" may be found in the open literature and in the structures community at large [1-6, for example]. The Strategic Defense Initiative Organization Materials and Structures (SDIO M&S) Program has proposed an alternative concept illustrated in Figure 1. Different types of sensors, either embedded in or attached to certain structures, are used to measure specific environmental features and to perform various subsystem diagnostics. These real-time passive devices can provide several functions such as structural health monitoring for identification, status, and propagation of cracks; threat detection measurements; natural environment measurements including radiation, atomic oxygen, loads, dynamic and static states, and thermal states; and monitoring of system states. The sensory information obtained from measurements and subsystem diagnostics is then processed and can be stored on-site or telemetered to another location. This information can also be utilized for static and dynamic structural control[a] via appropriate feedback loops using active structures containing actuators. The actuator devices can be static such as for shape control or dynamic such as for vibration suppression; acoustic and propulsion devices may also be used. Applications of this technology are only now becoming achievable as a result of developments in microprocessors and miniature sensors. Conceivable benefits include on-orbit system health monitoring and reporting and threat attack warning and assessment via a combination of sensory structures and information processing, and improved target tracking and hit-to-kill performance using a combination of sensory and active structures with information processing.

Although adaptive structures offer some very attractive features for these complex, autonomous systems there are many issues to be resolved. For sensory structures questions remain on sensor attachment methods; their durability in natural and threat environments; the number of sensors required[b] sensor placement and any associated constraints; choice of analog or digital output; general sensor performance; and effects of electromagnetic interactions. Information processing issues include selection of local and/or global control approaches; development of degradation protocol, and selection of a numerical/classical, symbolic/rule-based, or a neural network control theory approach. Issues for active structures include active material performance[c]; type of active device; methods for energy coupling; device durability in natural and threat environments; device placement and any associated constraints; and power requirements. And, finally, in order for system designers to accept this technology, it must be

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a Other properties of the system might also be controlled by such feedback loops: thermal properties, optical properties, electromagnetic properties, etc.[5]

b A large number of low sophistication sensors or a few smart sensors could be utilized.

c This includes, for example, the ability of piezoceramic materials to withstand high strains over many cycles.

Table 1. Materials and Structures Adaptive Structures Program Organization FY92

	Programs	Points Of Contact	Phone No.
Sensory Structures With Information Processing	**F1504 (Air Force)**		
	Health Monitoring of Moving Mechanical Assemblies	Mr. Karl Mecklenburg	513-255-2465
	N1504 (Navy)		
	Sensor Development for Micrometoroid/Debris Identification	Dr. Robert Badaliance	202-767-6380
	S1504 (SDIO)		
	Space Environmental Effects and Contamination Sensor Developments	Lt.Col. Michael Obal	703-693-1663
	E1504 (Department of Energy)		
	Sensory Structures	Dr. Mark Hodgson	505-667-6772
Sensory/Active Structures With Information Processing	**F1504 (Air Force)**		
	Passive Damping Application Technology	Dr. Alok Das	805-275-5412
	Vibration Suppression for Cryocoolers	Mr. Paul Lindquist	513-255-6622
	Advanced Materials Applications for Space Structures (AMASS)		
	Advanced Composites with Embedded Sensors and Actuators (ACESA)		
	Advanced Control Technology Experiment (ACTEX)		
	Modular Control Patch		
	High Frequency Passive Damping Strut Development		
	Optional PZT Passive Damping		
	Autonomous System Identification		
	Adaptive Structural Control		
	A1504 (Army)		
	Adaptive Thermal Isolator	Mr. Doug Ennis	205-955-1494
	Fast Acting Control Thruster		
	N1504 (Navy)		
	Large Deflection Ceramics for Actuators	Dr. Manfred Kahn	202-767-2216
	S1504 (SDIO)		
	System Identification Flight Experiment (INFLEX)	Dr. Fred Hadaegh	818-354-8777
	TechSat	Lt.Col. Michael Obal	703-693-1663

Table 2. A History of Tribology Problems in Space and Spacecraft System Impacts

Program	Tribological System	Problem	Impact
DMSP	OLS Sensor Launch Clamp	Seizure on Launch Pad	Single Point Failure, Prohibit Launch
NAV/GPS	Reaction Wheels (4/Satellite)	Torque/Temperature Runaway, Pointing Errors	Lubricant Loss and Starvation
Skylab	CMG Bearing	Failure	Premature Mission Failure
CDP	CMG Bearing	Failure	Loss of Mission
CDP	ATP Harmonic Drive	Excessive Wear	Degraded Mission, Possible Failure
CDP	Large CMGs (4/Satellite)	Runaway Torque, Cage Fracture, Lubricant Breakdown During Test	Life Test Failures @ $\leq$1/2 Life, Lubricant Starvation, Cage Instability Using Active Oiler
DSCS, CDP	Slip Ring	Excessive Noise	Communication Antenna Pointing Mission Compromised
Galileo	High Gain Antenna	Sticking of Antenna Rib Pins Due to Dry Lubricant Loss	Unfurled Antenna, Crippled Mission

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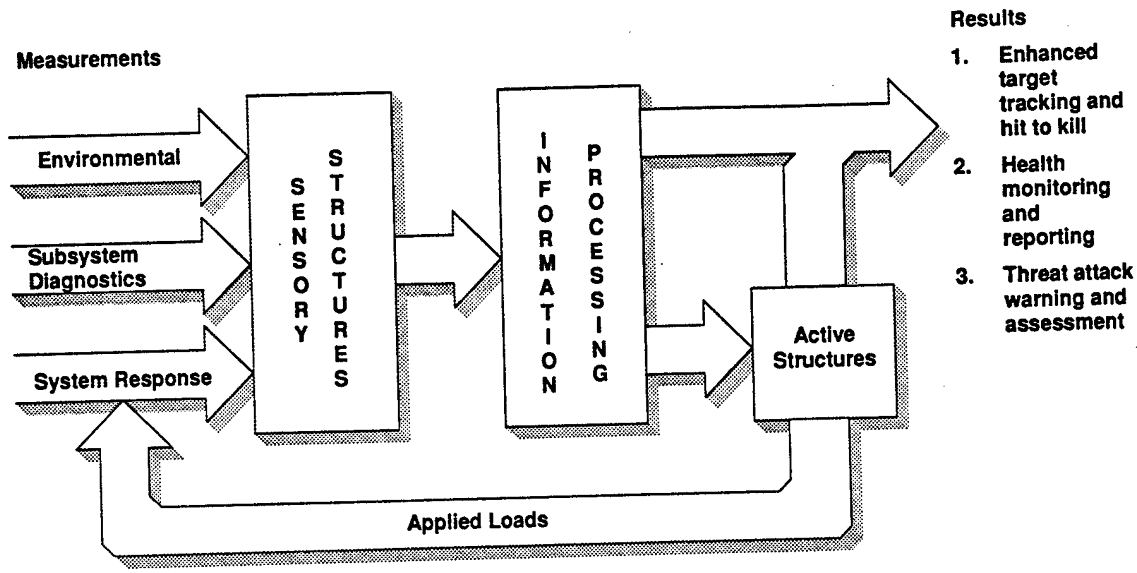

Figure 1. SDIO Proposed Concept for Adaptive Structures

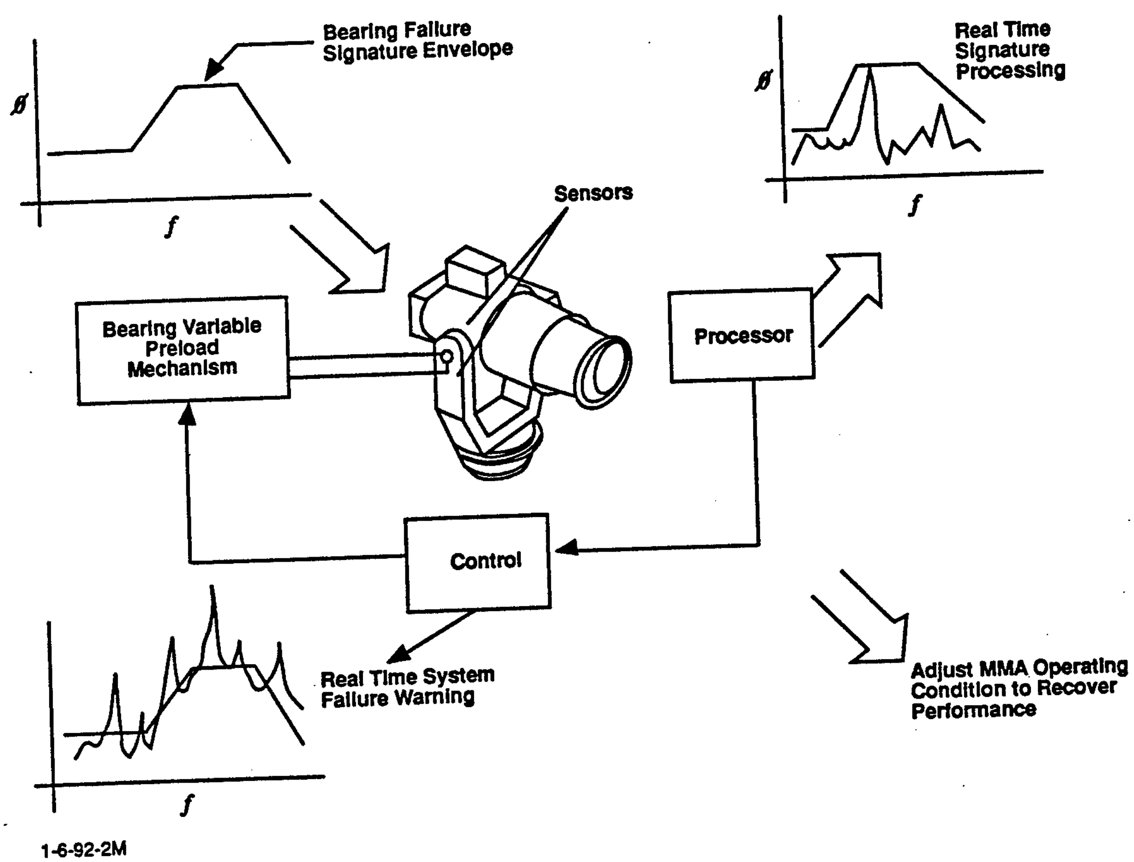

Figure 2. Schematic of Smart Tribomechanism

least intrusive to the design in terms of weight, power, and reliability. These issues are being addressed to some degree by the SDIO M&S Program as well as by other researchers.

M&S Adaptive Structures Programs

The M&S program intends to leverage outside research whenever possible. However, in order to provide the most appropriate adaptive structures technologies for the Strategic Defense Systems M&S efforts are currently focusing on the application of adaptive structures technology to provide SDS space elements: on-orbit system health monitoring and reporting and threat attack warning and assessment via a combination of sensory structures and information processing; improved target tracking and hit-to-kill performance via a combination of sensory and active structures with information processing. A M&S program chart showing points of contact and areas of research can be found in Table I. The general approach is through ground-based demonstrations leading to generic structural space experiments as appropriate. Examples of some of these programs follow.

Sensory Structures

Four areas M&S is currently focusing on in this area are real-time assessments of the state of (1) critical moving mechanical assemblies (MMAs) and momentum transfer devices; (2) micrometeoroids and debris (MM&D) identification; (3) real-time evaluation of critical materials deterioration and spacecraft contamination; and (4) threat attack warning and assessment.

Moving mechanical assemblies and momentum transfer devices are mission critical components on many DoD space assets: if the device fails the system cannot perform its mission. Examples are illustrated in Table 2. Wright Laboratories has initiated a M&S program to develop a health monitoring system for MMAs to help address potential failure problems. An example of a smart tribomechanism is illustrated in Figure 2. Major segments of the program include the following: (1) identification of vibration and torque signal signatures[d] for bearing structural mechanism and lubricant failures; (2) use of embedded or attached sensors to identify changes in acoustic or thermal signatures of the device; (3) development of an on-board control system to enable corrective action such as activation of adaptable bearing preload or of exercise protocol for fretting suppression; and (4) analyses of actual and predicted signatures to determine the expected remaining life of the device. This technology, applicable to any space assets having MMAs, would provide on-orbit capabilities to control or alter performance to extend system life.

One of SDIO's concerns for SDS elements is the degrading effect of MM&D or kinetic energy weapons (KEW) attack over time on critical sensor structures. To provide real-time assessment of these impacts, NRL is chartered to investigate technologies for impact detection, location identification, and damage assessment sensor systems. These sensor systems will be demonstrated via extensive ground and/or flight testing. M&S is leveraging ongoing work for DARPA on application of such sensor systems in submarine hulls for damage detection and analysis. The general approach is to detect, locate, and assess local structural damage and to determine the remaining structural performance capability. The operational requirements and specific environments need to be defined in order to select appropriate sensors and devices and locations, thereof. Acoustic emission and optical methods are being examined. Typical sensors may consist of piezoelectrics, capacitance-type sensors, and fiber optics.[e] A proposed acoustic emission technique uses a passive plate wave approach that recognizes source orientation effects and the true nature of the waveform as a function of structural geometry. Several types of fiber optic sensors are also being considered in a two-phase program: in Phase 1, speckle modulation and multiplexed interferometric arrays (shown in Figure 3) to detect occurrence of impact and location; and in Phase 2, distributed strain rosettes to detect deformation. The sensors, to be located on critical areas of the spacecraft, are also expected to be least intrusive to the system in terms of power and weight. This technology is applicable to a broad range of systems; examples are BP and BE optical sensor, antenna, heat exchanger, and solar array surfaces.

To actively determine the health of critical optical coatings and other materials and assess spacecraft self-contamination in the orbiting environment, M&S is developing the Space Active Modular Materials Experiments (SAMMES) program. The SAMMES modules, located on a generic spacecraft, and the system configuration are illustrated in Figure 4. Though not the original goal of this program, an additional benefit of SAMMES may be the capability to provide spacecraft with lightweight, low power, modular avionics for active health monitoring of mission critical materials. Recent findings from the Long Duration Exposure Facility (LDEF) suggest that contamination may pose serious problems for SDIO-like sensor systems. SAMMES may also offer the potential for active monitoring of contamination.

To field a fleet of surveillance and space-based interceptors or high value directed energy weapon (DEW) platforms will require continuous knowledge of the threat environment. Potential kill mechanisms range from the subtle (i.e., damage to parts of an electronic system from microwaves) to the direct (i.e., major structural damage from a nuclear explosion or a high-power laser). The external surface of the space asset provides an opportunity to embed or attach sensors that can identify and measure the threat. An additional benefit will be the ability to distinguish between system failures caused by natural or man-made environments. The M&S Program has initiated a program to develop a "Smart Skin": a prototype, light weight, low power sensor skin. These sensors will be able to measure radio frequency (RF), laser, and nuclear energy deposition on the satellite. These sensors include conformal antennae for RF detection, coated pyroelectric films for laser detection (Figure 5), and fiber optics for nuclear detection. The sensors and initial signal conditioning are embedded or attached to the spacecraft skin which provides thermal and space environment protection for the devices. Information from the skin is provided to on-orbit or ground-based systems that would identify the source of the energy and its damage capability. Since some of these sensors do require

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d These signature outputs are to be correlated with specific failure mechanisms. Under another M&S tribology program Lockheed is correlating torque signals with failure mechanisms of super-dense MoS_2-coated bearings.

e Fiber optics have advantages that include light weight, immunity from electro-magnetic interactions, electrical passivity, low power consumption, minimal leads in and out, and no direct current drift or bias offset. Disadvantages depend on the specific sensor type and may include inadequate sensitivity, requirement for integrated measurement over the whole fiber length, complex signal processing, fabrication of many reflective splices, requirement for multiple wavelength light sources, temperature sensitivity, and the need for high speed electronics.

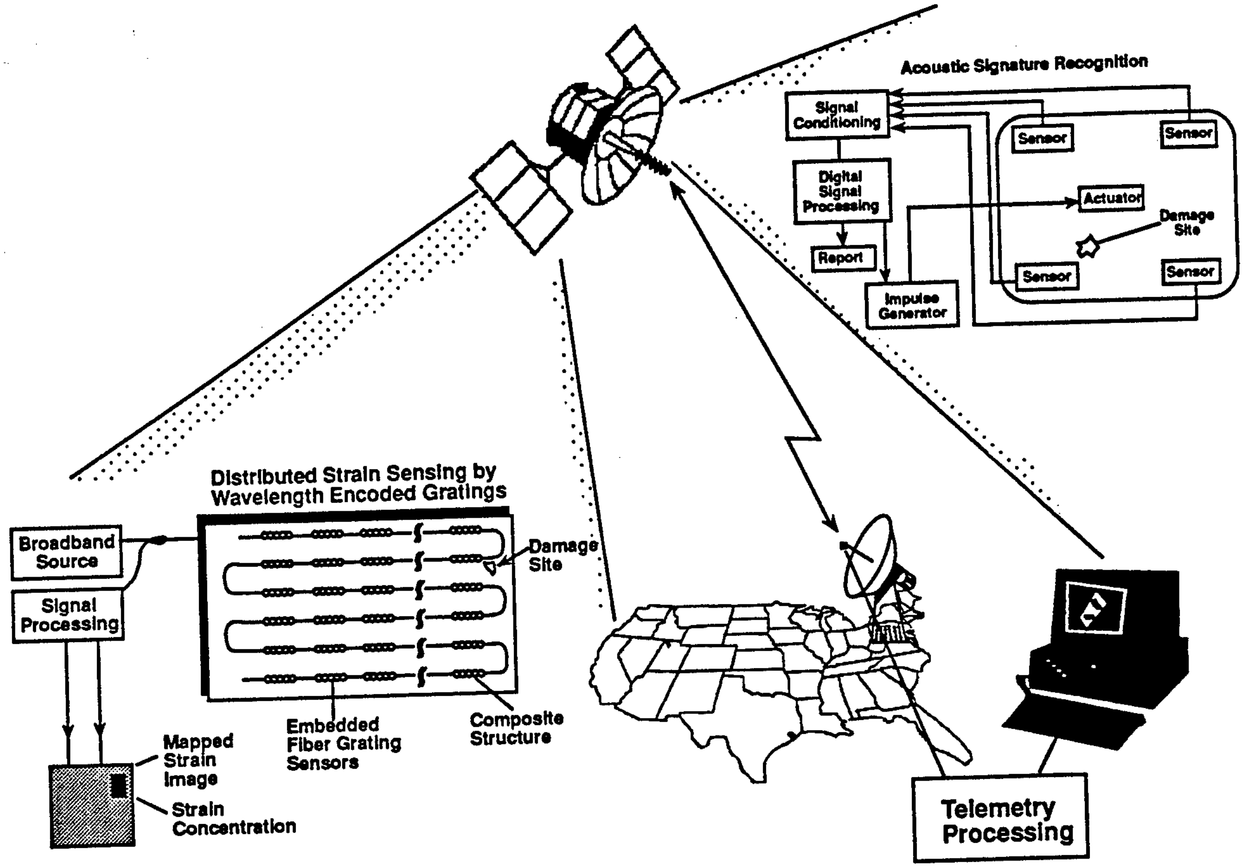

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Figure 3. Micrometeorite Impact Detection and Damage Assessment

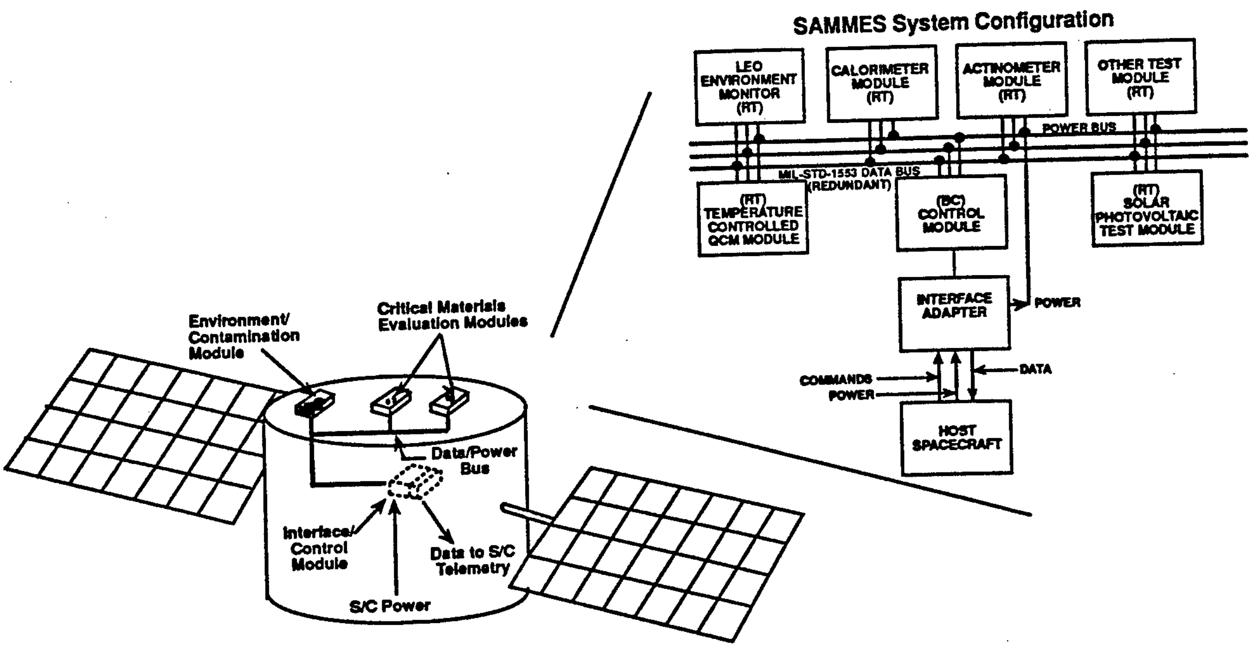

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Figure 4. Schematic of Critical Materials Health and System Contamination Monitoring Concept (SAMMES)

surface mounting, the skin itself must not interfere with the thermal balance of the spacecraft or require an excessive amount of surface area. A variety of materials have been examined for the skin structure. Combinations of advanced thermoplastics with shuttle tile ceramics appear promising for structural rigidity and thermal balance features. The advantage of real-time threat detection and assessment is the ability to provide critical information for the SDS fleet "user" to enhance survivability of those elements. This technology would be applicable to all US and Allied space assets.

Sensory/Active Structures

SDS elements require extreme tracking capabilities to meet mission performance goals. Sensor jitter from structural response seriously degrades this capability. Active and passive vibration suppression technologies provide a method of adaptable jitter control. Vibration control using piezoelectric devices as sensing and actuating elements has been in development for at least two decades. B.K. Wada's overview [5] of adaptive structures identifies research efforts undertaken in the early 1980's. This research has been significantly extended by industry and academia to the point where integration into fielded systems is more appropriate.

The ACESA (Advanced Composites with Embedded Sensors and Actuators) program was an early M&S initiative into the sensory/active structures arena. Overall goals for the program included design, fabrication, testing, and evaluation of composite components containing embedded sensors, actuators, and microprocessors. A number of parameters important in the selection of the sensors and actuators were identified: accuracy, dynamic range, frequency response, linearity, noise rejection, health monitoring capability, networking, device cost, survivability in natural and threat environments, technology readiness, embedding capability, and material processing conditions. A number of sensors and actuators, among which are fiber optics for sensors and shape memory alloys (SMAs) and piezoelectric ceramics for both sensors and actuators, were examined in light of the above parameters. The ability to use relatively simple drive electronics combined with other beneficial properties[f] led to the selection of piezoelectric ceramics for both sensors and actuators.

Some difficulties with embedding these and other devices into the composites were noted [7, 8]: fiber optic breakage, piezoelectric ceramic electrical insulation and cracking[g], mandrel thermal expansion, longitudinal mandrel bowing, and electrical insulation of shape memory alloy devices. Additional issues included mechanics of the device/structure interface during compression or tension, miniaturization for weight and power management, and central vs. distributed analog-to-digital (A/D) processing. Generally, though, characterization tests verified that the sensitivities and dynamic ranges of the sensors and actuators met the requirements derived from the system studies. The active structural control tests showed that the devices promoted significant damping and very short settling times. Good agreement was obtained between control simulations and experiments. Additional work is still needed, however, to address other issues such as active material development to obtain better actuator performance/watt, sensor and actuator placement, miniaturization of circuits and power conditioning, advanced control theory for adaptable control, neural network development for the "intelligent" aspects, and survivability in the space and threat environment.

Forward, Swigert, and Obal[9] completed one of the first successful demonstrations of the application of surface-mounted piezoceramic sensors and actuators for vibration control in a SDIO-like directed energy weapon system - the AF Airborne Laser Laboratory. A substantial amount of jitter reduction on a cavity resonator mirror was achieved with the combination of a passive tuned mass damper and an active rate feedback vibration control network that included piezoceramic devices. Unfortunately, the state of the technology at that time led to excessive high voltage power requirements. ACESA demonstrated an order of magnitude improvement in both actuator coupling and power requirements.

To meet current SDIO system power constraints using active vibration control, the performance of these active materials must be improved in order to obtain greater strains for a given input electrical load. To that end a task has been initiated at the Naval Research Laboratory (NRL) to improve toughness and durability of piezoelectric and electrostrictive actuator materials in order to obtain larger deflections, possibly up to 10 times that of conventional materials. The M&S Program is also looking for significant improvements in the number of cycles these materials can withstand under high/maximum strain conditions to address reliability concerns. Improvements in material reproducibility and manufacturing quality are also desired: i.e., it is difficult to obtain lead zirconate-lead titanate (PZT) materials having small variances in performance parameters from current vendors. Some interesting work is being done by Litton Optical Systems in conjunction with The Pennsylvania State University on the development of discrete multi-layer actuators made from lead magnesium niobate doped with lead titanate (PMN:PT)[10]. Results of their parametric studies showed a factor of ~3 improvement in achievable strain as well as improvements in material reproducibility and manufacturing yield. Included in the NRL task are specific research studies on methods to eliminate extrinsic voltage breakdown; the use of compositional chemistry, i.e., doped barium-containing PZT, to increase strain performance; and development of composite piezoelectric and electrostrictive materials containing whiskers or fibers to improve strength and toughness and to obtain higher c/a ratios. Methods for integrating these piezoelectric devices[h] into different actuator design configurations are also being investigated. Improved actuator materials would be applicable over a broad range of structural systems to provide better energy coupling.

Recognizing that the option of embedded sensors and actuators will not be permitted for all structures,[i] a concept

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f Piezoceramic sensor materials such as lead zirconate-lead titanate (PZT) exhibit low temperature and radiation sensitivity and high strain sensitivity. As sensors they have a large dynamic range and a frequency range exceeding the kHz level. In terms of actuation PZT devices have a quick response time coupled with high efficiency and a potentially large force authority.

g One solution to this difficulty was to encapsulate the PZT device with fiberglass or kevlar/epoxy prior to placement within the structure. This step is particularly crucial if the device is to be embedded into a graphite-reinforced composite since the fibers are conductive and will ground the high voltage circuits necessary to power the device.

h The Japanese are transitioning advanced piezoelectric devices into a number of commercial products, i.e., autofocus mechanisms for cameras, curtain pullers, aerators for fish tanks, laser printer heads, etc.

i For example, sensors and actuators may not be able to endure severe composite component manufacturing processes. Or, vibration problems may not have been anticipated or identified during the design process thus requiring a retrofitted solution.

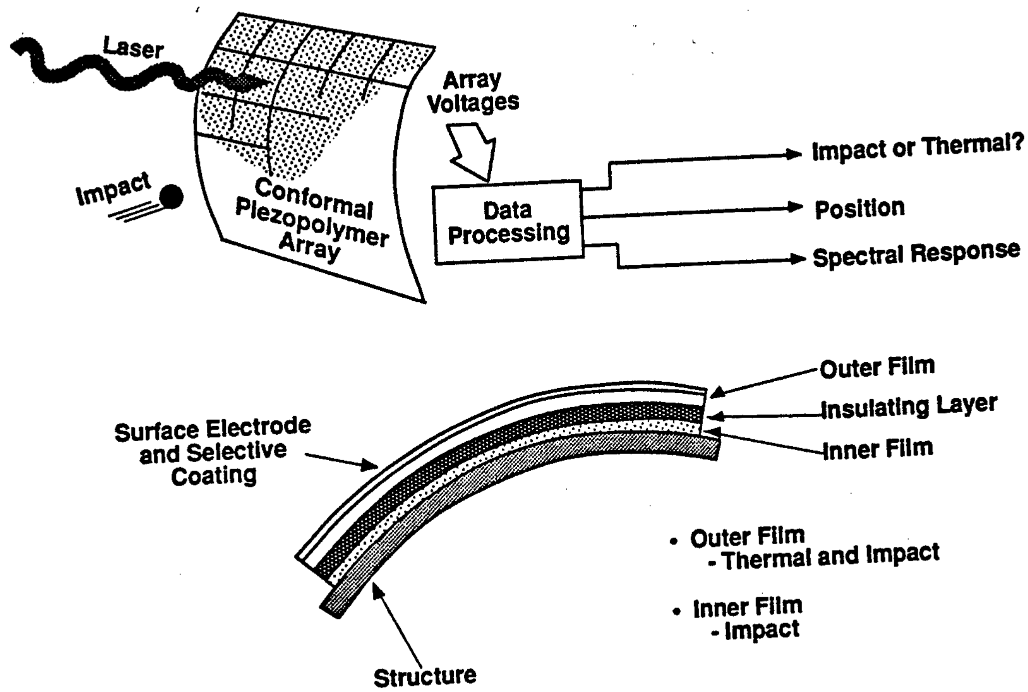

Figure 5. Schematic of Polymer Laser Sensor Skin.

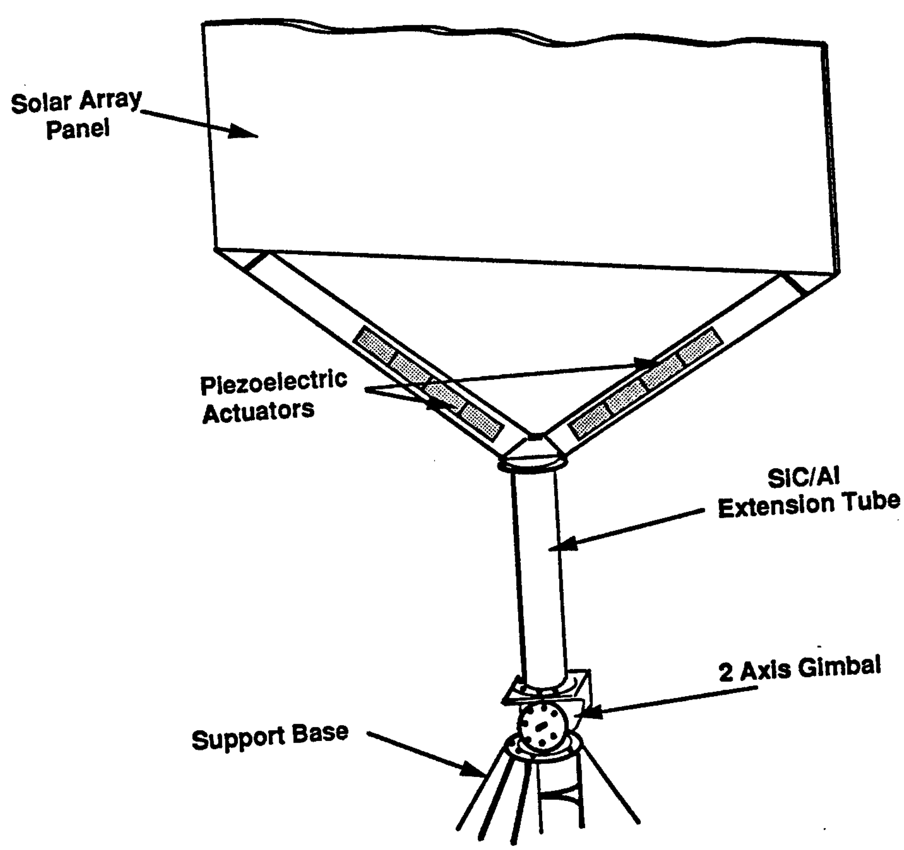

Figure 6. Schematic of AMASS Solar Array Structure

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for a space-durable modular patch is being developed. The patch integrates the sensor, actuator, controller, and power conditioning electronics into a single package that can be bonded to the structure and interfaced directly with the power system. An individual patch could exhibit local vibrational control or could work in concert with other patches in a global manner. Naturally, the patch must be space-durable and engineered in such a manner as to provide optimized coupling between the actuator and the structure. Expected benefits include significantly reduced control system weight and volume and, potentially, increased damping. This technology could be used to retrofit structural components for which embedding such devices is not an option: systems that undergo severe composite manufacturing process conditions or existing systems having vibration problems.

Such active vibration suppression concepts will be demonstrated on the Advanced Materials Application to Space Structures (AMASS) program. This program includes studies on dynamic decoupling of solar array support structure during rapid motions. Figure 6 is an illustration of the concept. Solar arrays, utilized on a number of existing satellites, are expected to be used for several SDI systems.

As mentioned previously, sensor jitter continues to be an issue with the advanced SDS assets. One of the greatest sources of sensor jitter, given a quiescent spacecraft, is the cryocooler itself[11, 12]. A project was initiated by M&S with JPL to address this difficult problem. A PZT device is being used to isolate the motion of a cryocooler cold finger on an existing, advanced Stirling cryocooler. JPL expects to demonstrate a factor of 2 to 5 reduction in transmitted vibratory forces in the 0 to 200 Hz range. Such a cryocooler system is expected to be flown on a UK satellite in FY93 to obtain space durability data in a high radiation environment. The technology is applicable to extremely small cryocooler systems intended for BP or BE where cryocooler-induced vibrations couple to the focal plane array sensor and lead to increased jitter.

To provide adaptive control of the sensor critical structures, the state of the plant must be known at all times. The M&S program is pursuing demonstrations of system and parameter identification (ID) technologies to meet this requirement. To address this issue researchers at the Jet Propulsion Laboratory (JPL)[13] have been examining methods for system ID of open and closed loop structural systems in space using active members on ground test articles. Experiments were performed on a cantilever truss structures. Their results indicate that active members can be used as an excitation source for on-orbit system identification for both closed and open loop systems. The active members provide a modal excitation source to aid in identification of low amplitude dynamic characteristics that are important in large, precision space structures. The difficulty of simulating on-orbit conditions on the ground for system/structural identification is well known. M&S is cooperating with the Phillips Laboratory in advancing such investigations via the Inexpensive Flight Experiment (INFLEX) program. On-orbit system and parameter ID experiments will be carried out on this space test bed in FY95.

The Advanced Control Technology Experiment (ACTEX) will demonstrate many of the adaptive structures technologies being investigated by M&S for improved tracking and hit-to-kill performance in space. In fact, the technology developed by the ACESA program provides the basis for this experiment. A small, composite, sensor-mounting tripod (Figure 7) with numerous embedded PZT sensors and actuators and corresponding control avionics will perform various vibration suppression and adaptive control experiments. Issues being examined include mechanics of piezoelectric device/structure interfaces, durability of the devices and structural materials in space, system identification of the structure, methods to change structural stiffness for re-identification, and miniaturization of power and control devices. Three years of on-orbit performance and space effects data are to be obtained via a space flight.

An ultra-fast (~1 msec), lightweight (~0.1 lb), linearly proportional control thruster (10 lb maximum force) called the Fast Acting Control Thruster (FACT), is being developed to improve vehicle attitude control for various SDS elements. The device, 0.625 inches (diameter) by 2.5 inches (length), consists of a piezoelectric/electrostrictive actuator, an elastomeric motion amplifier, and a cold gas, high force-gain valve. It is illustrated in Figure 8. A number of issues are being addressed in this program: active material hysteresis, general performance, and fatigue limits; active material stack design and manufacturing; motion amplification device performance; throat position determination and feedback; and reductions in size, weight and power requirements of drive electronics.

Transfer of an innovative spacecraft technology such as adaptive structures into developing spacecraft is the last step in the maturation of a technology and can be a formidable challenge. Spacecraft designers are justifiably cautious in accepting a new technology without flight heritage. Therefore, M&S has initiated plans for a program called TechSat. Its purpose is to provide an on-orbit, multi-discipline experiment platform for testing and validating promising technologies important to SDI space assets. An initial list of candidate experiments for TechSat includes several adaptive structure demonstrations that build on advances described elsewhere in this paper.

System advantages obtained from use of adaptive structures technologies are expected to include increased agility, pointing precision, stability, and shape/alignment control, all of which contribute to enhanced target tracking and hit-to-kill performance. These technologies would be applicable to a number of SDI systems such as BP, BE, Ground-Based Interceptor (GBI), E^2I, THAAD, and Neutral Particle Beam (NPB).

Summary

A number of potentially significant benefits for SDS elements using adaptive structures technologies have been identified: on-orbit system health monitoring and reporting, threat attack warning and assessment, improved target tracking and hit-to-kill performance. The current M&S programs were basically selected and initiated during FY91. Communication and coordination with the SDS program elements (BP, BE, etc.) is a continuing effort. All the M&S programs have planned intermediate ground demonstrations to assess their progress since many technical issues still need to be resolved. Additionally, all of the adaptive structures technologies developed under the M&S program must satisfy the necessary space and threat durability requirements as well as provide minimum weight, power, and reliability concerns for the system. Though some elements of adaptive structures technology are ready for demonstration there are issues that remain to be addressed. The SDIO M&S Program is leveraging existing efforts in and coordinating with other U.S. government programs and agencies to address some of the most important concerns.

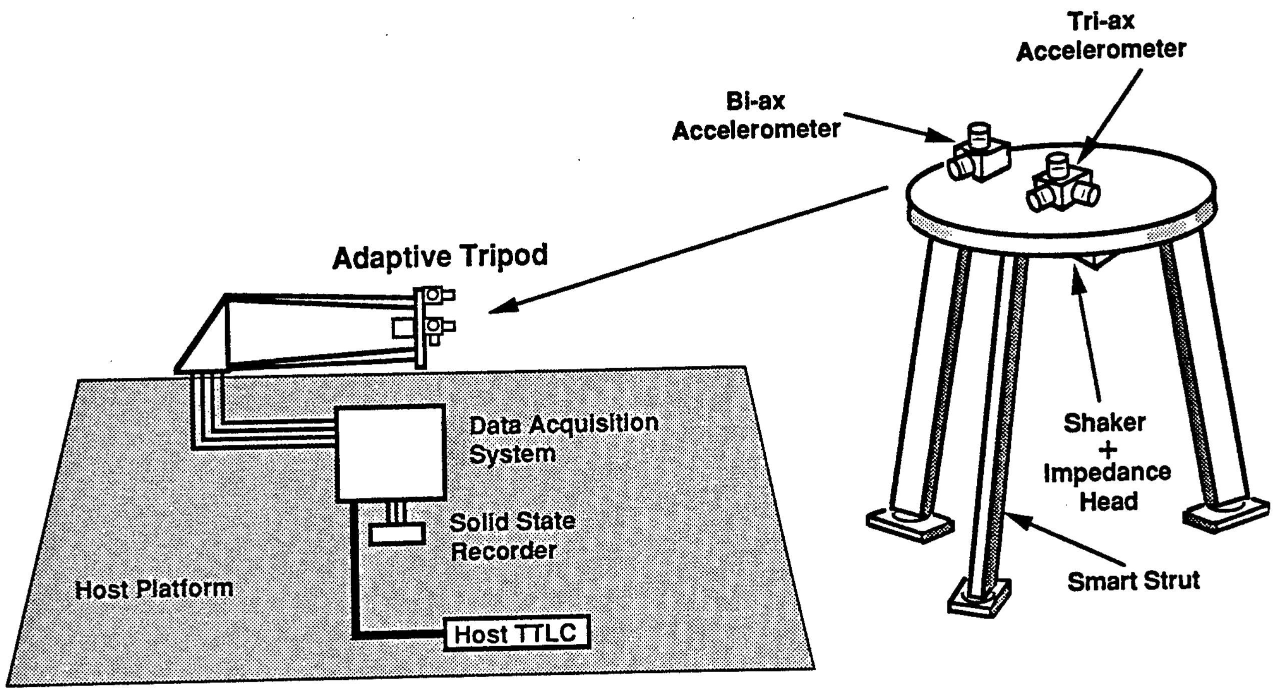

Figure 7. Schematic of Advanced Control Technology Experiment (ACTEX)

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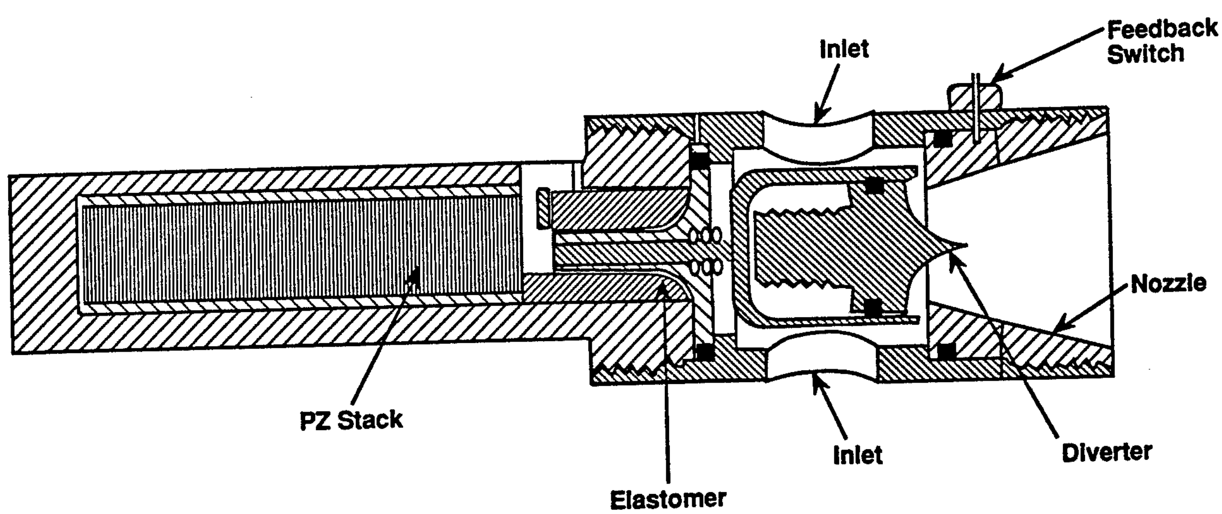

Figure 8. Schematic of Fast Acting Control Thruster.

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